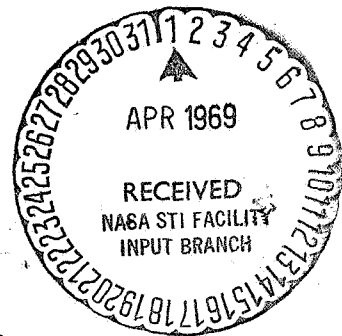


A MOLECULAR ORBITAL TREATMENT OF THE REACTIVITIES OF SUBSTITUTED
HETEROAROMATIC COMPOUNDS -- SUPERDELOCALIZABILITY

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Journal of the Chemical Society of Japan, Vol. 87, No. 7,
pp. 665-676, 1966.



FACILITY FORM 502

N69-71957

(ACCESSION NUMBER)

36

(PAGES)

(THRU)

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(CODE)

(NASA CR OR TMX OR AD NUMBER)

(CATEGORY)

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. NOVEMBER 1966

A MOLECULAR ORBITAL TREATMENT OF THE REACTIVITIES OF SUBSTITUTED
HETEROAROMATIC COMPOUNDS - SUPERDELOCALIZABILITY - (*1)

(Received December 22, 1960)

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ABSTRACT

The superdelocalizabilities in monosubstituted heteroaromatic compounds have been calculated as eight π -electron systems in terms of the functions of Coulomb and resonance integrals assigned for heteroatoms and substituents by the Hückel method.

The calculations have shown that (i) the effects of Coulomb integrals for substituents decrease on the order of $S_r^E > S_r^R > S_r^N$, (ii) the effects of Coulomb integrals for heteroatoms decrease in the order of $S_r^N > S_r^E > S_r^R$.

The relations of calculated superdelocalizabilities to the experimental results were discussed.

The value of the superdelocalizability of substituted heteroaromatic /665* compounds is computed as functions of Coulomb integrals and resonance integrals of heteroatoms and substituents by means of Hückel's method.

The effect of Coulomb integrals on the superdelocalizability decreases on the order of $S_r^E > S_r^R > S_r^N$.

The effect of heteroatoms on the superdelocalizability decreases on the order of $S_r^N > S_r^R > S_r^E$. The chemical reactivity of monosubstituted heteroaromatic compounds can be illustrated by superdelocalizability.

(*1) This paper is called "Molecular Orbital Treatment of Chemical Properties of Substituted Heteroaromatic Compounds, Report No. 2".

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* Numbers in the margin indicate pagination in the original foreign text.

1. INTRODUCTION

In the preceding report⁽¹⁾ we have considered how various stability properties of mono-substituted heteroaromatic compounds -- energy of the highest orbit, the order of π -combinations -- are dependent on the properties of heteroatoms and substituents by means of simple molecular orbital treatment. When the chemical reactivity of compounds of π -electron systems were discussed with the aid of the simple molecular orbital treatment, superdelocalizability and π -electron density were used with considerable success⁽²⁾.

In this report, we have investigated the manner in which the superdelocalizability of carbon atoms within mono-substituted heteroaromatic compounds depends on the properties of heteroatoms and substituents of compounds. We also have considered the chemical reactivity of substituted heteroaromatic compounds.

We have assumed that the properties of heteroatoms and substituents /666 are determined by both Coulomb integrals of these atoms and resonance integrals between these atoms and adjacent carbon atoms.^(*3)

As for superdelocalizability, there is one for electrophilic reactions (S_r^E), one for nucleophilic reactions (S_r^N), and one for radical reactions (S_r^R). These values are computed by Fukui's method⁽²⁾. Each atom of the compound is numbered similarly to the preceding report⁽¹⁾, as in Figure 1.

Also, the same symbols as are used in (Ref. 1) are employed. In this report, all substituted heteroaromatic compounds are treated as 8π -electron systems; the note 3 of (Ref. 1) may be referred to on this matter.

(1) Preceding report (Report No. 1). Ueno, Otsuji, Imoto. Nippon Kagaku Zasshi, Vol. 87, p. 659, 1966.

(2) K. Fukui, G. Nagata, T. Yonezawa, K. Morokuma. Bull. Chem. Soc., Japan, Vol. 34, p. 230, 1959.

(*3) In this report we assumed that the Coulomb integral α_X of heteroatom X for I and II type compounds is $\alpha + \beta$, $\alpha + 0.5\beta$, α , $\alpha - 0.5\beta$; the resonance integral β_{CX} between the heteroatom X and the adjacent carbon is β , 0.6β , 0.2β ; the Coulomb integral α_Y is $\alpha + 2\beta$, $\alpha + 1.5\beta$ and $\alpha + 0.5\beta$, and the resonance integral β_{CY} between the substituent Y and the adjacent carbon atom is β , 0.6β , 0.2β . Also, for type III compounds, we let α_X be $\alpha + 2\beta$, $\alpha + 0.5\beta$, α ; β_{CX} be 1.4β , β , 0.8β , α_Y be $\alpha + 2\beta$, $\alpha + \beta$, $\alpha + 0.5\beta$, α ; and β_{CY} be β .

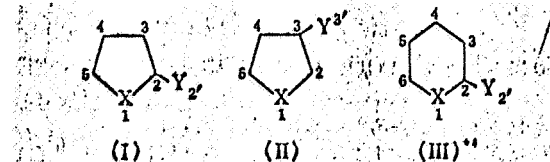


Figure 1

2. ELECTROPHILIC REACTIVITY S_r^E

2.1 Monohetero, 5-Membered Ring Components

2.1.1 Effect of Heteroatoms (*5)

In order to study the effect of heteroatoms, the Coulomb integral α_Y is equated with $\alpha + \beta$ and the resonance integral β_{CY} (between heteroatoms and adjacent carbon atoms) is equated with β . Then S_r^E is computed by changing the Coulomb integral α_X of heteroatoms from $\alpha + \beta$ to $\alpha - 0.5\beta$, and the resonance integral β_{CX} between heteroatoms and adjacent carbon atoms from β to 0.2β . The result is tabulated in Table 1, and the conclusions drawn from Table 1 are described below.

(1) Effect of α_X (*6)

1) The order of magnitude of S_r^E changes with α_X .

(i) When the absolute value of α_X is larger than α , S_r^E decreases in the order of $5^{th} > 3^{rd} > 4^{th}$ in the case of α -substituent, and in the order of $2^{nd} > 5^{th} > 4^{th}$ in the case of β -substituent. (*7)

(*4) When the substituent is at the 3^{rd} or 4^{th} position, the number of the substituent Y is described by $3'$ or $4'$.

(*5) Refer to footnote 4 of (Ref. 1).

(*6) Refer to footnote 5 of (Ref. 1).

(*7) When we assume that the absolute value of α_X is larger than "the neighborhood of α ", actually "the neighborhood of α " changes with the other parameters -- such as β_{CX} , α_Y , and β_{CY} . Strictly speaking, "the neighborhood of α " is only true when $\alpha_Y = \alpha + \beta$, $\beta_{CY} = \beta$ and β_{CY} is $\beta \sim 0.2\beta$. However, the tendency of S_r^E as a function of the absolute value of α_X is not affected. Thus "the neighborhood of α " only indicates an approximate measure. This footnote applies whenever we specify that a parameter is smaller or larger than a certain value.

TABLE 1

VALUE OF S_r^E WHEN α_X IS CHANGED TO β_{CX} AT THE MONOSUBSTITUTED,
5-MEMBERED RING (WHERE $\alpha_Y = \alpha + \beta$; $\beta_{CY} = \beta$)

α -substituent		S_1^E	S_2^E	S_3^E	S_4^E	S_5^E	S_6^E
β_{CX}	α_X						
β	$\alpha + \beta$	1.2930	1.6328	2.4317	1.5410	2.5962	3.0962
	$\alpha + 0.5\beta$	1.6884	1.9018	2.4257	1.8437	2.5426	3.4134
	α	2.4202	2.4987	2.4202	2.4796	2.4796	4.0648
	$\alpha - 0.5\beta$	4.4775	4.4298	2.4159	4.4515	2.4119	6.0519
0.6β	$\alpha + \beta$	1.6714	1.3677	2.4581	1.1958	2.7236	2.6999
	$\alpha + 0.5\beta$	2.6141	1.6031	2.4500	1.4610	2.6744	2.9832
	α	5.9735	2.6638	2.4397	2.5678	2.5970	4.1151
	$\alpha - 0.5\beta$	—	—	—	—	—	—
0.2β	$\alpha + \beta$	1.9584	1.1402	2.4877	0.9033	2.8333	2.3471
	$\alpha + 0.5\beta$	3.7674	1.1912	2.4853	0.9608	2.8222	2.4100
	α	50.1427	2.9947	2.4800	2.7813	2.7924	4.2431
	$\alpha - 0.5\beta$	—	—	—	—	—	—
β -substituent		S_1^E	S_2^E	S_3^E	S_4^E	S_5^E	S_6^E
β_{CX}	α_X						
β	$\alpha + \beta$	1.3477	2.5435	1.5334	1.4872	1.6621	3.0721
	$\alpha + 0.5\beta$	1.7481	2.4852	1.8482	1.4857	1.9068	3.4012
	α	2.4796	2.4202	2.4987	2.4202	2.4796	4.0648
	$\alpha - 0.5\beta$	4.5299	2.3550	4.4865	4.3934	4.3893	6.0628
0.6β	$\alpha + \beta$	1.7262	2.6855	1.1565	1.1724	1.4648	2.6310
	$\alpha + 0.5\beta$	2.6932	2.6277	1.4302	1.4225	1.6648	2.9275
	α	6.0794	2.5395	2.5530	2.5144	2.6773	4.0785
	$\alpha - 0.5\beta$	—	—	—	—	—	—
0.2β	$\alpha + \beta$	1.9705	2.8056	0.8469	0.9422	1.3254	2.2378
	$\alpha + 0.5\beta$	3.7936	2.7922	0.9043	0.9918	1.3641	2.3031
	α	50.2196	2.7526	2.7236	2.7911	3.1298	4.1417
	$\alpha - 0.5\beta$	—	—	—	—	—	—

Note (a): Because the highest orbital becomes an anti-bonding orbital (refer to Note b of the preceding Report 1), the value of S_r^E cannot be computed.

(ii) When the absolute value of α_X is smaller than α , S_r^E decreases in the order of 4th > 5th > 3rd for α -substituent, and in the order of 4th > 5th > 2nd for β -substituent.

2) Irrespective of β_{CX} , the following conclusions can be drawn:

(i) α -substituent; as the absolute value of α -substituents

increases, S_4^E decreases, but S_5^E and S_3^E slightly increase.

(ii) β -substituent; as the absolute value of α_X increases, S_2^E slightly increases, but S_4^E and S_5^E decrease. The decrease of S_4^E is larger than that of S_5^E .

(2) Effect of β_{CX} (*8)

1) The maximum site of S_r^E is determined by α_X for both α -substituent and β -substituent, and it does not depend on β_{CX} .

2) The effect of β_{CX} on S_r^E is different from that of α_X .

(i) When the absolute value of α_X is larger than α , S_4^E increases as the absolute value of β_{CX} increases for α -substituents, but S_3^E and S_5^E decrease. The decrease of S_5^E is larger than that of S_3^E . In the case of β -substituents, S_2^E decreases as the absolute value of β_{CX} increases, but S_4^E and S_5^E increase. The increase of S_4^E is larger than that of S_5^E , and the increase of S_3^E is larger than that of S_5^E .

(ii) When the absolute value of α_X is smaller than α , S_r^E decreases as the absolute value of β_{CX} increases for both α - and β -substituents. The rate of decrease is on the order of $S_5^E \sim S_4^E > S_3^E$ for α -substituent, and $S_5^E > S_2^E \sim S_4^E$ for β -substituent.

2.1.2 Effect of Substituent Base

In order to evaluate the effect of the substituent base, the Coulomb integral α_X of heteroatoms is equated with $\alpha + 0.5\beta$, and the resonance integral β_{CX} between heteroatoms and adjacent carbon atoms is equated with 0.6β . Then S_r^E is computed by changing the Coulomb integral α_Y from $\alpha + 2\beta$ to $\alpha + 0.5\beta$, and the resonance integral β_{CY} from $\alpha + 2\beta$ to $\alpha + 0.5\beta$. S_r^E is computed by changing the resonance integral β_{CY} between the substituent bases and the adjacent carbon atoms from β to 0.2β . The result is tabulated in Table 2. Since the maximum orbital becomes an antibonding orbital when the absolute value of α_Y becomes smaller than α and since S_r^E cannot be computed, α_Y is chosen in the range specified above. The conclusions drawn from Table 2 are described below.

(1) Effect of α_Y

1) Both for α - and β -substituents, the maximum site of S_r^E is determined by α_X , and it does not depend on α_Y .

(*8) Refer to footnote 7 of (Ref. 1).

TABLE 2

THE VALUE OF S_r^E WHEN α_Y AND β_{CY} ARE CHANGED IN MONOSUBSTITUTED,
5-MEMBERED RINGS (WHERE $\alpha_X = \alpha + 0.5\beta$, $\beta_{CX} = 0.6\beta$)

α -substituent							
β_{CY}	α_Y	S_1^E	S_2^E	S_3^E	S_4^E	S_5^E	S_6^E
β	$\alpha + 2\beta$	2.2519	1.4927	1.6659	1.3120	1.8909	1.2495
	$\alpha + 1.5\beta$	2.3528	1.5226	1.8891	1.3562	2.1148	1.7634
	$\alpha + \beta$	2.6141	1.6031	2.4500	1.4610	2.6744	2.9832
	$\alpha + 0.5\beta$	4.2549	2.1659	5.8593	2.0665	6.0772	9.9744
0.6β	$\alpha + 2\beta$	2.1144	1.4347	1.3419	1.2367	1.5544	1.0857
	$\alpha + 1.5\beta$	2.1398	1.4429	1.4005	1.2494	1.6140	1.4764
	$\alpha + \beta$	2.1981	1.4610	1.5307	1.2757	1.7450	2.2997
	$\alpha + 0.5\beta$	2.4263	1.5348	2.0184	1.3665	2.2320	5.1804
0.2β	$\alpha + 2\beta$	2.0628	1.4062	1.2144	1.2037	1.4183	1.0093
	$\alpha + 1.5\beta$	2.0651	1.4070	1.2199	1.2050	1.4240	1.3487
	$\alpha + \beta$	2.0702	1.4087	1.2316	1.2075	1.4359	2.0313
	$\alpha + 0.5\beta$	2.0875	1.4143	1.2697	1.2150	1.4741	4.1096
β -substituent							
β_{CY}	α_Y	S_1^E	S_2^E	S_3^E	S_4^E	S_5^E	S_6^E
β	$\alpha + 2\beta$	2.3071	1.8585	1.3001	1.2814	1.5150	1.2218
	$\alpha + 1.5\beta$	2.4181	2.0765	1.3371	1.3218	1.5595	1.7248
	$\alpha + \beta$	2.6932	2.6277	1.4302	1.4225	1.6648	2.9275
	$\alpha + 0.5\beta$	4.3524	6.0169	2.0157	2.0249	2.2715	9.8924
0.6β	$\alpha + 2\beta$	2.1362	1.5433	1.2336	1.2247	1.4395	1.0745
	$\alpha + 1.5\beta$	2.1664	1.6011	1.2439	1.2354	1.4522	1.4601
	$\alpha + \beta$	2.2321	1.7297	1.2661	1.2593	1.4786	2.2739
	$\alpha + 0.5\beta$	2.4723	2.2133	1.3491	1.3471	1.5695	5.1358
0.2β	$\alpha + 2\beta$	2.0653	1.4171	1.2035	1.2024	1.4065	1.0080
	$\alpha + 1.5\beta$	2.0682	1.4226	1.2045	1.2034	1.4078	1.3468
	$\alpha + \beta$	2.0743	1.4343	1.2066	1.2056	1.4103	2.0281
	$\alpha + 0.5\beta$	2.0934	1.4723	1.2132	1.2126	1.4177	4.1036

2) Irrespective of β_{CY} , S_r^E increases rapidly as the absolute value of α_Y decreases for both α - and β -substituents. The rate of increase becomes smaller in the order of $S_5^E > S_3^E > S_4^E$ for α -substituents, and in the order of $S_2^E > S_5^E > S_4^E$ for β -substituents. /668

(2) Effect of β_{CY}

1) The maximum site of S_r^E is determined by α_X for both α - and β -substituents, and it does not depend on β_{CY} .

2) Irrespective of α_Y , S_r^E increases as the absolute value of β_{CY} increases for both α - and β -substituents. The rate of increase becomes smaller in the order of $S_5^E > S_3^E > S_4^E$ for α -substituents,

and in the order of $S_2^E > S_5^E > S_4^E$ for β -substituents.

From these results, the following conclusions can be drawn:

1) The site undergoing electrophilic reactions is determined by the electric negativity of heteroatoms. When the electric negativity of heteroatoms is large (e.g., furane and thiophene derivatives), the 5th position of α -substituents and the 2nd position of β -substituents are most reactive. When the electric negativity of heteroatoms is small (e.g., $\alpha_X = \alpha - 0.5\beta$ with celenophene derivatives), the 4th position of α -substituents, and the 4th and 5th position of β -substituents are most reactive. According to the experiments, the electrophilic reaction is most reactive at the 5th position in the case of α -substituents such as furane or thiophene, except for the case when the substituent base is a strong electron-absorbing base, such as nitro-base. Also, the 2nd position is most reactive in the case of β -substituents.⁽³⁾ Therefore, the experimental results can be illustrated by the value of S_r^E for both α - and β -substituents.

2) Not only the overlapping of wave functions of heteroatoms /669 and substituent bases with those of adjacent carbon atoms, but also the electric negativity of substituent bases, affects the reactivity. However, they are not influential enough to move the reaction site.

2.2 Monohetero, 6-Membered Ring Compounds

Let the resonance integral β_{CY} between substituent bases and adjacent carbon atoms be β . Then we change the Coulomb integral α_X from $\alpha + 2\beta$ to α , the resonance integral β_{CX} from 1.4β to 0.8β , and the Coulomb integral α_Y from $\alpha + 2\beta$ to α . We can then compute S_r^E accordingly. The results are shown in Tables 3, 4, 5 and 6. We also give the conclusions drawn from these tables below.

2.2.1 α -Substituent

(1) The maximum site of S_r^E does not depend on α_X , β_{CX} and α_Y , and it becomes largest at the 3rd position succeeded by the 5th position.

(2) When $\beta_{CX} = \beta$ (e.g., pyridine), S_3^E and S_5^E decrease as the absolute value of α_X increases, irrespective of α_Y . The rate of decrease is on the order of $S_5^E > S_3^E$. The effect of α_X on S_4^E and S_6^E is dependent on α_Y .

(3) When $\alpha_X = \alpha + 0.5\beta$ (e.g., pyridine), S_3^E and S_5^E increase as the absolute value of β_{CX} increases, irrespective of α_Y . The rate of

(3) A. A. Morton, "The Chemistry of Heterocyclic Compounds", McGraw Hill, New York, 1946.

TABLE 3

THE VALUE OF S_r^E WHEN α_X , β_{CX} AND α_Y ARE CHANGED IN
MONOSUBSTITUTED, 6-MEMBERED RINGS

i) α -substituent ($\alpha_X = \alpha + 0.5\beta$, $\beta_{CY} = \beta$)		S_1^E	S_2^E	S_3^E	S_4^E	S_5^E	S_6^E	S_7^E
β_{CX}	α_Y							
1.4 β	$\alpha + 2\beta$	0.6574	0.6368	1.0077	0.7188	0.9888	0.6928	1.0367
	$\alpha + \beta$	0.7582	0.6004	1.2067	0.7188	1.1729	0.6951	2.0064
	$\alpha + 0.5\beta$	0.9602	0.5679	1.6009	0.7218	1.5512	0.6989	3.7321
	α	4.4960	0.6152	8.5228	0.8283	8.4446	0.8040	31.6413
β	$\alpha + 2\beta$	0.9442	0.6586	1.0055	0.7199	0.9745	0.7447	1.0279
	$\alpha + \beta$	1.1082	0.6100	1.1973	0.7203	1.1414	0.7580	1.9399
	$\alpha + 0.5\beta$	1.4281	0.5730	1.5432	0.7293	1.4612	0.7802	3.4346
	α	4.5778	0.6782	4.7373	0.9053	4.6091	0.9798	16.3483
0.8 β	$\alpha + 2\beta$	1.1892	0.6666	1.0042	0.7169	0.9625	0.7777	1.0194
	$\alpha + \beta$	1.4046	0.6082	1.1887	0.7184	1.1137	0.8005	1.8791
	$\alpha + 0.5\beta$	1.8059	0.5709	1.4927	0.7356	1.3834	0.8403	3.1765
	α	4.5834	0.7224	3.3511	0.9648	3.1842	1.1102	10.6853
ii) α -substituent ($\alpha_X = \alpha + 2\beta$, $\beta_{CY} = \beta$)		S_1^E	S_2^E	S_3^E	S_4^E	S_5^E	S_6^E	S_7^E
β_{CX}	α_Y							
β	$\alpha + 2\beta$	0.6881	0.4902	1.0038	0.5686	0.9265	0.6807	0.9523
	$\alpha + \beta$	0.7520	0.4561	1.1522	0.6106	1.0257	0.7617	1.6200
	$\alpha + 0.5\beta$	0.8626	0.4794	1.3405	0.6950	1.1693	0.8830	2.4112
	α	1.2867	0.7812	1.8809	1.0686	1.6462	1.3145	4.5894

increase is on the order of $S_5^E > S_3^E$. On the contrary, S_4^E and S_6^E become smaller on the order of $S_6^E < S_4^E$.

(4) Irrespective of α_X and β_{CX} , S_r^E decreases as the absolute value of α_Y increases. The rate of decrease is on the order of $S_3^E \sim S_5^E \gg S_4^E \sim S_6^E$.

2.2.2 β -Substituent

(1) The maximum site of S_r^E changes with β_{CX} , irrespective of α_X and α_Y . It is at the 4th position when β_{CX} is equal to 1.4 β , but it is at the 2nd position when β_{CX} is 0.8 β .

(2) When $\beta_{CX} = \beta$, S_r^E decreases as the absolute value of α_X increases, irrespective of α_Y . The rate of decrease is on the order of $S_4^E > S_6^E > S_2^E \gg S_5^E$.

(3) When $\alpha_X = \alpha + 0.5\beta$, S_4^E and S_5^E decrease as the absolute value of β_{CX} increases, irrespective of α_Y , but S_2^E and S_6^E decrease.

TABLE 4

THE VALUE OF S_r^E WHEN α_X , β_{CX} , AND α_Y ARE CHANGED IN
MONOSUBSTITUTED, 6-MEMBERED RINGS

i) β -substituent ($\alpha_X = \alpha + 0.5\beta$, $\beta_{CY} = \beta$)								
β_{CX}	α_Y	S_1^E	S_2^E	S_3^E	S_4^E	S_5^E	S_6^E	S_7^E
1.4β	$\alpha + 2\beta$	0.5787	0.8628	0.7948	0.8893	0.8365	0.8434	1.0739
	$\alpha + \beta$	0.5769	1.0848	0.7532	1.1093	0.8337	1.0500	2.1389
	$\alpha + 0.5\beta$	0.5746	1.5633	0.7106	1.5873	0.8304	1.5125	4.2025
	α^0	—	—	—	—	—	—	—
β	$\alpha + 2\beta$	0.8160	0.9125	0.7899	0.8868	0.8299	0.8801	1.0737
	$\alpha + \beta$	0.8136	1.1411	0.7493	1.1012	0.8269	1.0810	2.1399
	$\alpha + 0.5\beta$	0.8101	1.6276	0.7072	1.5725	0.8233	1.5366	4.2061
	α^0	—	—	—	—	—	—	—
0.8β	$\alpha + 2\beta$	1.0178	0.9455	0.7861	0.8812	0.8249	0.9012	1.0734
	$\alpha + \beta$	1.0153	1.1898	0.7462	1.0900	0.8216	1.0965	2.1405
	$\alpha + 0.5\beta$	1.0110	1.6760	0.7047	1.5538	0.8179	1.5446	4.2092
	α^0	—	—	—	—	—	—	—
ii) β -substituent ($\alpha_X = \alpha + 2\beta$, $\beta_{CY} = \beta$)								
β_{CX}	α_Y	S_1^E	S_2^E	S_3^E	S_4^E	S_5^E	S_6^E	S_7^E
β	$\alpha + 2\beta$	0.6488	0.8113	0.7844	0.6821	0.8197	0.7212	1.0742
	$\alpha + \beta$	0.6487	1.0661	0.7456	0.8733	0.8160	0.8988	2.1443
	$\alpha + 0.5\beta$	0.6470	1.5852	0.7044	1.3147	0.8120	1.3242	4.2196
	α^0	—	—	—	—	—	—	—

Note (a): Since the maximum orbital becomes an anti-bonding orbital [refer to Note 6 of (Ref. 1)], S_r^E cannot be calculated.

(4) Irrespective of α_X and β_{CX} , S_5^E slightly increases as the absolute value of α_Y increases, but S_2^E , S_4^E , and S_6^E decrease.

2.2.3 γ -Substituent

(1) The maximum site of S_r^E does not depend on α_X , α_Y and β_{CX} .

(2) When $\beta_{CX} = \beta$, S_3^E and S_2^E decrease, irrespective of α_Y as the absolute value of α_X increases.

(3) When $\alpha_X = \alpha + 0.5\beta$, S_3^E increases irrespective of α_Y as the absolute value of β_{CX} increases, but S_2^E decreases.

(4) Irrespective of α_X and β_{CX} , S_3^E and S_2^E decrease as the absolute value of β_{CX} increases. The rate of decrease of S_3^E is larger than that of S_2^E .

TABLE 5

THE VALUE OF S_r^E WHEN α_X , β_{CX} AND α_Y ARE CHANGED IN
MONOSUBSTITUTED, 6-MEMBERED RINGS

i) γ -substituent ($\alpha_X = \alpha + 0.5\beta$, $\beta_{CY} = \beta$)							
β_{CX}	α_Y	S_1^E	S_2^E	S_3^E	S_4^E	S_5^E	S_6^E
1.4 β	$\alpha + 2\beta$	0.6521	0.6842	1.0001	0.6697	1.0407	
	$\alpha + \beta$	0.7447	0.6842	1.1975	0.6298	2.0121	
	$\alpha + 0.5\beta$	0.9372	0.6873	1.5914	0.5940	3.7372	
	α	4.4545	0.7940	8.5148	0.6368	31.6407	
β	$\alpha + 2\beta$	0.9404	0.7244	0.9857	0.6603	1.0310	
	$\alpha + \beta$	1.0954	0.7247	1.1658	0.6122	1.9496	
	$\alpha + 0.5\beta$	1.4034	0.7338	1.5010	0.5739	3.4531	
	α	4.5315	0.9106	4.6780	0.6745	16.3832	
0.8 β	$\alpha + 2\beta$	1.1874	0.7479	0.9735	0.6481	1.0215	
	$\alpha + \beta$	1.3936	0.7492	1.1378	0.5938	1.8910	
	$\alpha + 0.5\beta$	1.7835	0.7664	1.4223	0.5569	3.2032	
	α	4.5419	0.9973	3.2498	0.7043	10.7398	
ii) γ -substituent ($\alpha_X = \alpha + 2\beta$, $\beta_{CX} = \beta$)							
β_{CX}	α_Y	S_1^E	S_2^E	S_3^E	S_4^E	S_5^E	S_6^E
β	$\alpha + 2\beta$	0.6958	0.6176	0.9370	0.4685	0.9580	
	$\alpha + \beta$	0.7588	0.6589	1.0484	0.4397	1.6425	
	$\alpha + 0.5\beta$	0.8669	0.7438	1.2051	0.4614	2.4547	
	α	1.2873	1.1245	1.7029	0.7550	4.6620	

From these results we obtain the following conclusions:

(1) For each of the α -, β - and γ -substituents, α_Y affects S_r^E at the o- and p-position through substituent bases. The effect of substituent bases on S_r^E depends on α_X and β_{CX} , as well as on the relative site of substituent bases, heteroatoms, and carbon atoms inside the ring. /670

(2) When heteroatoms are at the o- and p-position with respect to substituent bases, S_r^E strongly depends on the electric negativity of heteroatoms at the o- and p-position (the sites of strong electrophilic reactivity due to large S_r^E). As the electric negativity of heteroatoms increases, S_r^E at these sites decreases. Therefore, S_r^E at the 3rd and 5th position of α -substituents, as well as at the 3rd position of the γ -substituents, is smaller than that of the β -substituents at the 2nd position.

(3) We nitrated various oxypyridines in a mixed acid at 25°C (70°C for γ -substituent) and obtained the rate of reactivity as shown in Figure 2(4). In these compounds, pyridine bases became reaction cores

(4) Veno, Hirai, Asakawa, Imoto (unpublished).

TABLE 6

THE VALUE OF S_r^E WHEN α_Y IS CHANGED IN MONOSUBSTITUTED,
6-MEMBERED RINGS (WHERE $\alpha_X = \alpha$, $\beta_{CY} = \beta$)

α_Y	S_1^E	S_2^E	S_3^E	S_4^E	S_5^E	α_Y	S_1^E	S_2^E	S_3^E	S_4^E	S_5^E
$\alpha + 2\beta$	0.9950	0.8312	1.0062	0.7895	1.0730	$\alpha + 0.5\beta$	1.6656	0.8248	1.7057	0.7066	4.2011
$\alpha + \beta$	1.2027	0.8283	1.2273	0.7485	2.1375	α	—	—	—	—	—

Note (a): Since the maximum orbital is an anti-bonding orbital S_r^E cannot be computed [refer to Note 6 (Ref. 1)].

themselves. In the figure, S_r^E of every carbon atom is also described inside the parentheses. Except for the α -substituent, S_r^E agrees with experimental results, as may be observed from Figure 2. There are some problems for α -substituents, and we will report on this in a subsequent paper.

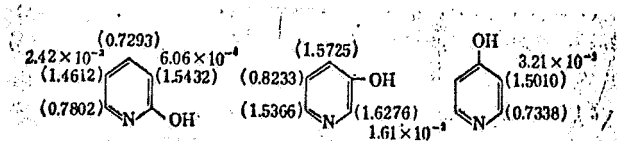


Figure 2

S_r^E of Various Oxypyridines and the Reaction
Rate of Nitration (l , mol^{-1} , sec^{-1})

Parameters used in computation: $\alpha_N = \alpha + 0.5\beta$,
 $\beta_{CN} = \beta$, $\alpha_{OH} = \alpha + 0.5\beta$, $\beta_{C-OH} = \beta$.

3. NUCLEOPHILIC REACTIVITY S_r^N

3.1 Monohetero, 5-Membered Ring Compounds

3.1.1 Effect of Heteroatoms

Using the same parameters as in 2.1.1 for S_r^E , we may compute S_r^N . The results are shown in Table 7, and the conclusion drawn from the table is described below.

TABLE 7

THE VALUE OF S_r^N WHEN α_Y AND β_{CX} ARE CHANGED IN
MONOSUBSTITUTED, 5-MEMBERED RINGS (WHERE $\alpha_Y = \alpha + \beta$, $\beta_{CY} = \beta$)

α - substituent								
β_{CX}	α_X	S_1^N	S_2^N	S_3^N	S_4^N	S_5^N	S_6^N	S_7^N
β	$\alpha + \beta$	0.2930	0.6328	0.4317	0.5410	0.5962	0.09623	
	$\alpha + 0.5\beta$	0.3551	0.5685	0.4257	0.5103	0.5426	0.08008	
	α	0.4202	0.4987	0.4202	0.4796	0.4796	0.06478	
	$\alpha - 0.5\beta$	0.4775	0.4298	0.4159	0.4515	0.4119	0.05190	
0.6β	$\alpha + \beta$	0.2009	0.8383	0.4581	0.6664	0.7236	0.1705	
	$\alpha + 0.5\beta$	0.2885	0.7659	0.4500	0.6238	0.6744	0.1460	
	α	0.4179	0.6638	0.4397	0.5670	0.5971	0.1151	
	$\alpha - 0.5\beta$	—	—	—	—	—	—	
0.2β	$\alpha + \beta$	0.03532	1.0633	0.4877	0.8264	0.8333	0.2702	
	$\alpha + 0.5\beta$	0.06374	1.0431	0.4853	0.8127	0.8222	0.2618	
	α	0.1428	0.9947	0.4800	0.7813	0.7924	0.2431	
	$\alpha - 0.5\beta$	—	—	—	—	—	—	
β - substituent								
β_{CX}	α_X	S_1^N	S_2^N	S_3^N	S_4^N	S_5^N	S_6^N	S_7^N
β	$\alpha + \beta$	0.3477	0.5435	0.5334	0.4872	0.6621	0.07209	
	$\alpha + 0.5\beta$	0.4148	0.4852	0.5148	0.4524	0.5735	0.06791	
	α	0.4796	0.4202	0.4987	0.4202	0.4796	0.06478	
	$\alpha - 0.5\beta$	0.5299	0.3550	0.4865	0.3934	0.3893	0.06283	
0.6β	$\alpha + \beta$	0.2556	0.6855	0.6271	0.6430	0.9354	0.1016	
	$\alpha + 0.5\beta$	0.3676	0.6277	0.5930	0.5853	0.8276	0.09033	
	α	0.5239	0.5395	0.5530	0.5144	0.6773	0.07850	
	$\alpha - 0.5\beta$	—	—	—	—	—	—	
0.2β	$\alpha + \beta$	0.04740	0.8056	0.7700	0.8653	1.2485	0.1609	
	$\alpha + 0.5\beta$	0.08992	0.7922	0.7562	0.8436	1.2160	0.1550	
	α	0.2196	0.7526	0.7236	0.7911	1.1298	0.1417	
	$\alpha - 0.5\beta$	—	—	—	—	—	—	

(1) Effect of α_X

1) The order of magnitude of S_r^N depends on α_X .

(i) When the absolute value of α_X is larger than α , S_r^N becomes smaller in the order of 5th > 4th > 3rd for the α -substituent, and in the order of 5th > 2nd > 4th for the β -substituent.

(ii) When the absolute value of α_X is smaller than α , S_r^N becomes smaller in the order of 4th > 5th > 3rd for the α -substituent, and in the order of 5th > 4th > 2nd for the β -substituent.

2) Both for α - and β -substituents, S_r^N increases as the absolute value of α_X increases. The rate of increase becomes smaller

TABLE 8

THE VALUE OF S_r^N WHEN α_Y AND β_{CY} ARE CHANGED IN
MONOSUBSTITUTED, 5-MEMBERED RINGS (WHERE $\alpha_X = \alpha + 0.5\beta$,
 $\beta_{CX} = 0.6\beta$)

α -substituent		S_1^N	S_2^N	S_3^N	S_4^N	S_5^N	S_6^N
β_{CY}	α_Y						
β	$\alpha + 2\beta$	0.3288	0.8004	0.4928	0.6197	0.7178	0.07644
	$\alpha + 1.5\beta$	0.3119	0.7879	0.4742	0.6215	0.6998	0.1035
	$\alpha + \beta$	0.2885	0.7659	0.4500	0.6238	0.6744	0.1460
	$\alpha + 0.5\beta$	0.2549	0.7259	0.4193	0.6265	0.6372	0.2144
0.6β	$\alpha + 2\beta$	0.3831	0.8114	0.5628	0.6134	0.7753	0.02957
	$\alpha + 1.5\beta$	0.3755	0.8078	0.5536	0.6142	0.7671	0.04147
	$\alpha + \beta$	0.3640	0.8007	0.5403	0.6154	0.7545	0.06199
	$\alpha + 0.5\beta$	0.3447	0.7854	0.5196	0.6171	0.7333	0.1013
0.2β	$\alpha + 2\beta$	0.4137	0.8125	0.6042	0.6101	0.8081	0.003386
	$\alpha + 1.5\beta$	0.4127	0.8122	0.6030	0.6102	0.8071	0.004825
	$\alpha + \beta$	0.4113	0.8115	0.6012	0.6103	0.8055	0.007428
	$\alpha + 0.5\beta$	0.4086	0.8099	0.5981	0.6106	0.8025	0.01291
β -substituent		S_1^N	S_2^N	S_3^N	S_4^N	S_5^N	S_6^N
β_{CY}	α_Y						
β	$\alpha + 2\beta$	0.3840	0.6854	0.6078	0.5891	0.8227	0.04869
	$\alpha + 1.5\beta$	0.3773	0.6615	0.6024	0.5871	0.8248	0.06494
	$\alpha + \beta$	0.3676	0.6277	0.5930	0.5853	0.8276	0.09033
	$\alpha + 0.5\beta$	0.3524	0.5769	0.5757	0.5849	0.8315	0.1324
0.6β	$\alpha + 2\beta$	0.4049	0.7642	0.6104	0.6014	0.8162	0.01841
	$\alpha + 1.5\beta$	0.4021	0.7542	0.6088	0.6003	0.8170	0.02510
	$\alpha + \beta$	0.3979	0.7392	0.6058	0.5990	0.8183	0.03622
	$\alpha + 0.5\beta$	0.3907	0.7146	0.5997	0.5977	0.8202	0.05668
0.2β	$\alpha + 2\beta$	0.4162	0.8069	0.6098	0.6087	0.8128	0.002089
	$\alpha + 1.5\beta$	0.4159	0.8057	0.6097	0.6085	0.8129	0.002879
	$\alpha + \beta$	0.4154	0.8039	0.6094	0.6084	0.8131	0.004230
	$\alpha + 0.5\beta$	0.4144	0.8007	0.6088	0.6081	0.8133	0.006854

in the order of $S_5^N \sim S_4^N \gg S_3^N$ for the α -substituents, and in the order of $S_5^N > S_2^N > S_4^N$ for the β -substituents.

(2) Effect of β_{CX}

1) The order of magnitude of S_r^N is determined by α_X for the α -substituent, and it changes in the order of $S_5^N > S_4^N > S_3^N$, irrespective of β_{CX} . In the case of the β -substituent, it is determined by β_{CX} . When the absolute value of β_{CX} is larger than 0.4β , it becomes smaller in the order of $S_5^N > S_2^N > S_4^N$, and when the absolute value of β_{CX} is smaller than 0.4β , it becomes smaller in the order of $S_5^N > S_4^N > S_2^N$.

TABLE 9

THE VALUE OF S_r^N WHEN α_X , β_{CX} , α_Y ARE CHANGED IN
MONOSUBSTITUTED, 6-MEMBERED RINGS

i) α -substituent (where $\alpha_X = \alpha + 0.5\beta$, $\beta_{CX} = \beta$)								
β_{CX}	α_Y	S_1^N	S_2^N	S_3^N	S_4^N	S_5^N	S_6^N	S_7^N
1.4 β	$\alpha + 2\beta$	0.5338	0.7604	0.7654	0.8424	0.7466	0.8165	0.06758
	$\alpha + \beta$	0.5184	0.7203	0.7367	0.8387	0.7028	0.8150	0.1263
	α	0.4960	0.6152	0.6828	0.8283	0.6046	0.8040	0.2813
β	$\alpha + 2\beta$	0.7089	0.8939	0.7702	0.9552	0.7392	0.9800	0.08667
	$\alpha + \beta$	0.6642	0.8322	0.7528	0.9425	0.6969	0.9802	0.1621
	α	0.5778	0.6782	0.7373	0.9053	0.6091	0.9798	0.3483
0.8 β	$\alpha + 2\beta$	0.8333	1.0225	0.7765	1.0728	0.7347	1.1336	0.1084
	$\alpha + \beta$	0.7510	0.9350	0.7704	1.0452	0.6954	1.1273	0.2059
	α	0.5834	0.7224	0.7911	0.9648	0.6242	1.1102	0.4453
ii) α -substituent (where $\alpha_X = \alpha + 2\beta$, $\beta_{CY} = \beta$)								
β_{CX}	α_Y	S_1^N	S_2^N	S_3^N	S_4^N	S_5^N	S_6^N	S_7^N
β	$\alpha + 2\beta$	0.4881	1.2902	0.8038	1.3686	0.7265	1.4807	0.1523
	$\alpha + \beta$	0.4187	1.1229	0.8189	1.2773	0.6923	1.4283	0.2866
	α	0.2867	0.7812	0.8809	1.0686	0.6462	1.3146	0.5894

2) For both α - and β -substituents, S_r^N decreases as the /671 absolute value of β_{CX} increases, irrespective of α_X . The rate of decrease becomes smaller in the order of $S_5^N \sim S_4^N \gg S_3^N$ for the α -substituents, and in the order of $S_5^N > S_4^N > S_2^N$ for the β -substituents.

3.1.2 Effect of Substituent Base

The same parameters as used in (2.1.2) to compute S_r^E are used in computing S_r^N . The results are tabulated in Table 8, and the conclusions associated with this are described below.

(1) Effect of α_Y

1) For both α - and β -substituents, the order of magnitude of S_r^N is determined by α_X , and it is independent of α_Y .

2) For both α - and β -substituents, S_r^N decreases, irrespective of α_Y , as the absolute value of β_{CY} increases. The rate of decrease becomes smaller in the order of $S_5^N > S_3^N \gg S_4^N$ for the α -substituent, and in the order of $S_2^N \gg S_5^N \sim S_4^N$ for the β -substituents.

TABLE 10

THE VALUE OF S_r^N WHEN α_X , β_{CX} , α_Y ARE CHANGED IN
MONOSUBSTITUTED, 6-MEMBERED RINGS

i) β -substituent (where $\alpha_X = \alpha + 0.5\beta$, $\beta_{CY} = \beta$)								
β_{CX}	α_Y	S_1^N	S_2^N	S_3^N	S_4^N	S_5^N	S_6^N	S_7^N
1.4 β	$\alpha + 2\beta$	0.5787	0.7403	0.7948	0.7668	0.8365	0.7210	0.07388
	$\alpha + \beta$	0.5769	0.7124	0.7532	0.7368	0.8337	0.6776	0.1389
	$\alpha + 0.5\beta$	0.5746	0.6909	0.7106	0.7148	0.8304	0.6401	0.2025
β	$\alpha + 2\beta$	0.8160	0.9125	0.7899	0.8868	0.8299	0.8801	0.07371
	$\alpha + \beta$	0.8136	0.8911	0.7493	0.8512	0.8269	0.8310	0.1399
	$\alpha + 0.5\beta$	0.8101	0.8776	0.7072	0.8225	0.8233	0.7866	0.2061
0.8 β	$\alpha + 2\beta$	1.0178	1.0861	0.7861	1.0218	0.8249	1.0418	0.07345
	$\alpha + \beta$	1.0153	1.0714	0.7463	0.9806	0.8216	0.9871	0.1405
	$\alpha + 0.5\beta$	1.0110	1.0666	0.7047	0.9444	0.8179	0.9352	0.2092
ii) β -substituent (where $\alpha_X = \alpha + 2\beta$, $\beta_{CY} = \beta$)								
β_{CX}	α_Y	S_1^N	S_2^N	S_3^N	S_4^N	S_5^N	S_6^N	S_7^N
β	$\alpha + 2\beta$	0.6488	1.5613	0.7844	1.4321	0.8197	1.4712	0.07418
	$\alpha + \beta$	0.6487	1.5661	0.7456	1.3733	0.8160	1.3988	0.1443
	$\alpha + 0.5\beta$	0.6470	1.5852	0.7044	1.3147	0.8120	1.3242	0.2196

(2) Effect of β_{CY}

1) For both α - and β -substituents, the order of magnitude of S_r^N does not depend on β_{CY} . Namely, it is determined by α_X .

2) For both α - and β -substituents, S_r^N decreases as the absolute value of β_{CY} increases, irrespective of α_Y . The rate of decrease is in the order of $S_5^N \sim S_3^N > S_4^N$ for the α -substituent, and in the order of $S_2^N \gg S_5^N \sim S_4^N$ for the β -substituent.

From these results, the following conclusions are reached:

1) The site undergoing nucleophilic reactions depends on the electric negativity of heteroatoms for both α - and β -substituents. For a larger electric negativity, the 5th position is most reactive, while for a smaller electric negativity the 4th position is most reactive.

2) For both α - and β -substituents, the electric negativity of substituent bases, as well as the overlapping of wave functions of substituent bases with those of adjacent carbon atoms, has a small effect on S_r^N . The reactivity of substituted ring compounds is determined by the kind of heteroatoms. The larger the electric negativity of heteroatoms,

TABLE 11

THE VALUE OF S_r^N WHEN α_X , β_{CX} , α_Y ARE CHANGED IN
MONOSUBSTITUTED, 6-MEMBERED RINGS

i) r-substituent (where $\alpha_X = \alpha + 0.5\beta$, $\beta_{cy} = \beta$)						
β_{cx}	α_Y	S_1^N	S_2^N	S_3^N	S_4^N	S_5^N
1.4β	$\alpha + 2\beta$	0.5285	0.8078	0.7578	0.7933	0.07157
	$\alpha + \beta$	0.5049	0.8041	0.7275	0.7497	0.1320
	α	0.4545	0.7940	0.6748	0.6368	0.2807
β	$\alpha + 2\beta$	0.7051	0.9596	0.7504	0.8956	0.08982
	$\alpha + \beta$	0.6509	0.9471	0.7213	0.8345	0.1719
	α	0.5315	0.9106	0.6780	0.6745	0.3832
0.8β	$\alpha + 2\beta$	0.8316	1.1038	0.7458	1.0040	0.1105
	$\alpha + \beta$	0.7400	1.0760	0.7195	0.9206	0.2178
	α	0.5418	0.9973	0.6898	0.7043	0.4998
ii) r-substituent (where $\alpha_X = \alpha + 2\beta$, $\beta_{cy} = \beta$)						
β_{cx}	α_Y	S_1^N	S_2^N	S_3^N	S_4^N	S_5^N
β	$\alpha + 2\beta$	0.4958	1.4176	0.7370	1.2685	0.1580
	$\alpha + \beta$	0.4254	1.3256	0.7150	1.1064	0.3092
	α	0.2873	1.1245	0.7029	0.7550	0.6620

and the smaller the overlapping of wave functions of heteroatoms with those of adjacent carbon atoms, the larger S_r^N becomes and the more reactive it becomes.

3) The properties of heteroatoms and substituent bases have less effect on S_r^N than they do on S_r^E .

3.2 Monohetero, 6-Membered Ring Compounds

Using the same parameters as in the case of S_r^E of monohetero 6-membered ring compounds, we may compute S_r^N , and the results are depicted in Tables 9, 10, 11 and 12. The conclusions associated with this are presented below.

3.2.1 α -Substituent

(1) The maximum site of S_r^N depends on β_{CX} , irrespective of α_Y and α_X . When β_{CX} is 1.4β , it is at the 4th position, but at the 6th position for 0.8β .

(2) When $\beta_{CX} = \beta$, S_3^N , S_4^N , and S_6^N increase, irrespective of α_Y , as the absolute value of α_X increases. The rate of increase is in the order of $S_6^N > S_4^N \gg S_3^N$. The effect of α_X on S_5^N depends on α_Y .

TABLE 12

THE VALUES OF S_r^N WHERE α_Y IS CHANGED IN MONOSUBSTITUTED,
6-MEMBERED RINGS (WHERE $\alpha_X = \alpha$, $\beta_{CY} = \beta$)

α_Y	S_1^N	S_2^N	S_3^N	S_4^N	S_5^N	S_6^N
$\alpha + 2\beta$	0.7450	0.8312	0.7562	0.7895	0.07303	
$\alpha + \beta$	0.7027	0.8283	0.7273	0.7485	0.1375	
$\alpha + 0.5\beta$	0.6656	0.8248	0.7057	0.7066	0.2011	

(3) When $\alpha_X = \alpha + 0.5\beta$, S_3^N , S_4^N and S_6^N decrease irrespective of α_Y , as the absolute value of β_{CX} increases. The rate of decrease is in the order of $S_6^N > S_4^N \gg S_3^N$. The effect of β_{CX} on S_5^N is dependent on α_Y .

(4) Irrespective of α_X and β_{CX} , S_4^N , S_5^N and S_6^N increase as the absolute value of α_Y increases. The rate of increase is in the order of $S_5^N > S_4^N > S_6^N$. The effect of α_Y on S_3^N is dependent on α_X and β_{CX} .

3.2.2 β -Substituent

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(1) The maximum site of S_r^N changes with β_{CX} , irrespective of α_Y . When the absolute value of α_X becomes larger and that of β_{CX} becomes smaller, it is at the 2nd position. When the absolute value of α_X becomes smaller and that of β_{CX} becomes larger, it moves to the 5th position.

(2) When $\beta_{CX} = \beta$, S_5^N decreases irrespective of α_Y as the absolute value of α_X increases, but S_2^N , S_4^N and S_6^N increase. The rate of increase is in the order of $S_2^N > S_6^N > S_4^N$. /673

(3) When $\alpha_X = \alpha + 0.5\beta$, S_5^N increases irrespective of α_Y as the absolute value of β_{CX} increases, but S_2^N , S_4^N and S_6^N decrease. The rate of decrease is in the order of $S_2^N > S_6^N > S_4^N$.

(4) Irrespective of α_X and β_{CX} , S_r^N increases as the absolute value of α_Y increases. The effect of α_Y on S_r^N is smaller than that of β_{CX} and α_X on S_r^N .

3.2.3 γ -Substituent

(1) The maximum site of S_r^N is at the 2nd position and is

TABLE 13

THE VALUE OF S_r^R WHEN α_X AND β_{CX} ARE CHANGED IN
MONOSUBSTITUTED, 5-MEMBERED RINGS (WHERE $\alpha_Y = \alpha = \beta$, $\beta_{CY} = \beta$)

α -substituent							
β_{CX}	α_X	S_1^R	S_2^R	S_3^R	S_4^R	S_5^R	$S_{1,2}^R$
β	$\alpha + \beta$	0.7930	1.1328	1.4317	1.0410	1.5962	1.5962
	$\alpha + 0.5\beta$	1.0218	1.2351	1.4257	1.1770	1.5426	1.7467
	α	1.4202	1.4987	1.4202	1.4796	1.4796	2.0648
	$\alpha - 0.5\beta$	2.4775	2.4300	1.4159	2.4515	1.4119	3.0519
0.6β	$\alpha + \beta$	0.9361	1.1030	1.4581	0.9311	1.7236	1.4352
	$\alpha + 0.5\beta$	1.4513	1.1844	1.4500	1.0424	1.6744	1.5646
	α	3.1957	1.6638	1.4397	1.5678	1.5971	2.1151
	$\alpha - 0.5\beta$	—	—	—	—	—	—
0.2β	$\alpha + \beta$	0.9969	1.1018	1.4877	0.8649	1.8333	1.3087
	$\alpha + 0.5\beta$	1.9156	1.1172	1.4853	0.8867	1.8222	1.3359
	α	25.1427	1.9947	1.4800	1.7813	1.7924	2.2431
	$\alpha - 0.5\beta$	—	—	—	—	—	—
β -substituent							
β_{CX}	α_X	S_1^R	S_2^R	S_3^R	S_4^R	S_5^R	$S_{1,2}^R$
β	$\alpha + \beta$	0.8477	1.5435	1.0334	0.9872	1.1621	1.5721
	$\alpha + 0.5\beta$	1.0814	1.4852	1.1815	1.1191	1.2402	1.7346
	α	1.4796	1.4202	1.4987	1.4202	1.4796	2.0648
	$\alpha - 0.5\beta$	2.5299	1.3550	2.4865	2.3934	2.3893	3.0628
0.6β	$\alpha + \beta$	0.9909	1.6855	0.8918	0.9077	1.2001	1.3663
	$\alpha + 0.5\beta$	1.5304	1.6277	1.0116	1.0039	1.2462	1.5089
	α	3.3017	1.5395	1.5530	1.5144	1.6773	2.0785
	$\alpha - 0.5\beta$	—	—	—	—	—	—
0.2β	$\alpha + \beta$	1.0090	1.8056	0.8085	0.9038	1.2870	1.1994
	$\alpha + 0.5\beta$	1.9418	1.7922	0.8303	0.9177	1.2900	1.2290
	α	25.2196	1.7526	1.7236	1.7911	2.1298	2.1417
	$\alpha - 0.5\beta$	—	—	—	—	—	—

Note (a): Since the maximum orbital becomes an anti-bonding orbital [refer to note 6 of (Ref. 1)], S_r^R cannot be computed.

independent of α_X , β_{CX} , and α_Y .

(2) When $\beta_{CX} = \beta$, S_2^N increases irrespective of α_Y as the absolute value of α_X increases. The effect of α_X on S_3^N is dependent on α_Y .

(3) When $\alpha_X = \alpha + 0.5\beta$, S_2^N decreases irrespective of α_Y as the absolute value of β_{CX} increases. But the effect of β_{CX} on S_3^N is dependent on α_Y .

(4) Irrespective of α_X and β_{CX} , S_2^N and S_3^N increase as the absolute value of α_Y increases. The effect of α_Y on S_r^N is smaller than that of β_{CX} and α_X on S_r^N .

The following conclusions may be drawn from these results:

(1) For every α -, β - and γ -substituent, the effect of the electric negativity of substituent bases on S_r^N is smaller than that of the electric negativity of heteroatoms; this also holds true for the effect on the overlapping of wave functions of heteroatoms with those of adjacent carbon atoms.

(2) The larger the electric negativity of heteroatoms and the smaller the overlapping of wave functions of heteroatoms with those of adjacent carbon atoms, the larger the values of S_2^N , S_4^N and S_6^N become.

4. RADICAL REACTIVITY S_r^R

4.1 Monohetero 5-Membered Ring Compounds

4.1.1 Effect of Heteroatoms

The same parameters used for S_r^E in 2.1.1 are used in computing S_r^R . The results are shown in Table 13, and the conclusions associated with this are described below.

(1) Effect of α_X

1) The order of magnitude of α_X depends on S_r^R .

(i) When the absolute value of α_X is larger than α , S_r^R becomes smaller in the order of 5th > 3rd > 4th for the α -substituent, and in the order of 2nd > 5th > 4th for the β -substituent.

(ii) When the absolute value of α_X is smaller than α , S_r^R becomes smaller in the order of 4th > 5th > 3rd for the α -substituent, and in the order of 5th > 4th > 2nd for the β -substituent.

2) Irrespective of β_{CX} , S_4^R decreases as the absolute value of α_X increases for the α -substituent. The rate of increase of S_5^R is greater than that of S_3^R .

In the case of the β -substituent, S_2^R increases as the absolute value of α_X increases, but S_5^R and S_4^R decrease. The rate of decrease of S_4^R is less than that of S_5^R .

TABLE 14

THE VALUE OF S_r^R WHEN α_X AND β_{CX} ARE CHANGED IN
MONOSUBSTITUTED, 5-MEMBERED RINGS (WHERE $\alpha_X = \alpha + 0.5\beta$, $\beta_{CX} = 0.6\beta$)

α -substituent							
β_{CX}	α_X	S_1^R	S_2^R	S_3^R	S_4^R	S_5^R	S_6^R
β	$\alpha + 2\beta$	1.2903	1.1466	1.0794	0.9658	1.3043	0.6630
	$\alpha + 1.5\beta$	1.3323	1.1552	1.1817	0.9888	1.4073	0.9335
	$\alpha + \beta$	1.4513	1.1844	1.4500	1.0424	1.6744	1.5646
	$\alpha + 0.5\beta$	1.2549	1.4459	3.1393	1.3465	3.3572	5.0944
0.6β	$\alpha + 2\beta$	1.2488	1.1230	0.9524	0.9251	1.1649	0.5576
	$\alpha + 1.5\beta$	1.2577	1.1254	0.9771	0.9318	1.1906	0.7589
	$\alpha + \beta$	1.2811	1.1309	1.0355	0.9456	1.2498	1.1808
	$\alpha + 0.5\beta$	1.3854	1.1601	1.2690	0.9918	1.4826	2.6409
0.2β	$\alpha + 2\beta$	1.2382	1.1093	0.9093	0.9069	1.1132	0.5064
	$\alpha + 1.5\beta$	1.2389	1.1096	0.9115	0.9076	1.1155	0.6768
	$\alpha + \beta$	1.2407	1.1101	0.9164	0.9089	1.1207	1.0194
	$\alpha + 0.5\beta$	1.2481	1.1121	0.9339	0.9128	1.1383	2.0613
β -substituent							
β_{CX}	α_X	S_1^R	S_2^R	S_3^R	S_4^R	S_5^R	S_6^R
β	$\alpha + 2\beta$	1.3455	1.2719	0.9540	0.9353	1.1689	0.6352
	$\alpha + 1.5\beta$	1.3977	1.3690	0.9698	0.9545	1.1921	0.8949
	$\alpha + \beta$	1.5304	1.6277	1.0116	1.0039	1.2462	1.5089
	$\alpha + 0.5\beta$	2.3524	3.2969	1.2957	1.3049	1.5515	5.0124
0.6β	$\alpha + 2\beta$	1.2705	1.1537	0.9220	0.9130	1.1278	0.5465
	$\alpha + 1.5\beta$	1.2843	1.1776	0.9264	0.9178	1.1346	0.7426
	$\alpha + \beta$	1.3150	1.2345	0.9360	0.9291	1.1484	1.1551
	$\alpha + 0.5\beta$	1.4315	1.4640	0.9744	0.9724	1.1948	2.5962
0.2β	$\alpha + 2\beta$	1.2407	1.1120	0.9067	0.9055	1.1097	0.5051
	$\alpha + 1.5\beta$	1.2420	1.1142	0.9071	0.9060	1.1103	0.6748
	$\alpha + \beta$	1.2448	1.1191	0.9080	0.9070	1.1117	1.0162
	$\alpha + 0.5\beta$	1.2539	1.1365	0.9110	0.9103	1.1155	2.0552

(2) Effect of β_{CX}

1) The order of magnitude of S_r^R depends on α_X for both α - and β -substituents, and is independent of β_{CX} .

2) The effect of β_{CX} on S_r^R is dependent on α_X .

(i) When the absolute value of α_X is larger than α , S_4^R increases as the absolute value of β_{CX} increases for the α -substituent, but S_3^R and S_5^R decrease. The rate of decrease of S_5^R is larger than that of S_3^R . As for the β -substituent, S_4^R increases as the absolute value of β_{CX} increases, but S_2^R and S_5^R decrease. The rate of decrease of S_2^R is larger than that of S_5^R .

TABLE 15

THE VALUE OF S_r^R WHEN α_X , β_{CX} , α_Y ARE CHANGED IN
MONOSUBSTITUTED, 6-MEMBERED RINGS

i) α -substituent (where $\alpha_X = \alpha + 0.5\beta$, $\beta_{cy} = \beta$)								
β_{cx}	α_Y	S_1^R	S_2^R	S_3^R	S_4^R	S_5^R	S_6^R	S_7^R
1.4 β	$\alpha + 2\beta$	0.5956	0.6986	0.8866	0.7806	0.8677	0.7547	0.5521
	$\alpha + \beta$	0.6383	0.6604	0.9717	0.7788	0.9378	0.7551	1.0664
	α	2.4960	0.6152	4.6028	0.8283	4.5246	0.8040	15.9613
β	$\alpha + 2\beta$	0.8266	0.7763	0.8879	0.8376	0.8569	0.8623	0.5573
	$\alpha + \beta$	0.8864	0.7211	0.9750	0.8314	0.9192	0.8691	1.0510
	α	2.5778	0.6782	2.7373	0.9053	2.6091	0.9798	8.3483
0.8 β	$\alpha + 2\beta$	1.0112	0.8446	0.8904	0.8949	0.8486	0.9557	0.5639
	$\alpha + \beta$	1.0778	0.7716	0.9795	0.8818	0.9045	0.9639	1.0425
	α	2.5834	0.7224	2.0711	0.9648	1.9042	1.1102	5.5653
ii) α -substituent (where $\alpha_X = \alpha + 2\beta$, $\beta_{cy} = \beta$)								
β_{cx}	α_Y	S_1^R	S_2^R	S_3^R	S_4^R	S_5^R	S_6^R	S_7^R
β	$\alpha + 2\beta$	0.5881	0.8902	0.9038	0.9686	0.8265	1.0807	0.5523
	$\alpha + \beta$	0.5854	0.7895	0.9856	0.9440	0.8590	1.0949	0.9533
	α	0.7867	0.7812	1.3809	1.0686	1.1462	1.3146	2.5894

(ii) When the absolute value of α_X is smaller than α , /674
 S_r^R of both α - and β -substituents decreases as the absolute value of β_{CX} increases. The rate of decrease is in the order of $S_5^R > S_4^R > S_3^R$ for the α -substituent, and in the order of $S_5^R > S_4^R > S_2^R$ for the β -substituent.

4.1.2 Effect of Substituent Base

Using the same parameters as in the case of S_r^E in (2.1.2), we may compute S_r^R . The results are shown in Table 14, and the conclusions are described below.

(1) Effect of α_Y

1) For both α - and β -substituents, the order of magnitude of S_r^R is determined by α_X , and is independent of α_Y .

2) For both α - and β -substituents, S_r^R rapidly increases as the absolute value of α_Y decreases. The rate of increase becomes smaller in the order of $S_5^R > S_3^R > S_4^R$ for the α -substituent, and in the order of $S_2^R > S_5^R > S_4^R$ for the β -substituent.

TABLE 16

THE VALUE OF S_r^R WHEN α_X , β_{CX} , α_Y ARE CHANGED IN
MONOSUBSTITUTED, 6-MEMBERED RINGS

i) β -substituent (where $\alpha_X = \alpha + 0.5\beta$, $\beta_{CY} = \beta$)								
β_{CX}	α_Y	S_1^R	S_2^R	S_3^R	S_4^R	S_5^R	S_6^R	S_7^R
1.4 β	$\alpha + 2\beta$	0.5787	0.8016	0.5739	0.8281	0.8365	0.7322	0.7948
	$\alpha + \beta$	0.5769	0.8986	1.1389	0.9231	0.8337	0.8638	0.7532
	α	0.5746	1.1271	2.2025	1.1518	0.8330	1.0763	0.7107
β	$\alpha + 2\beta$	0.8160	0.9125	0.5737	0.8868	0.8299	0.8801	0.7899
	$\alpha + \beta$	0.8136	1.0161	1.1399	0.9762	0.8269	0.9560	0.7493
	α	0.8101	1.2526	2.2061	1.1975	0.8233	1.1616	0.7072
0.8 β	$\alpha + 2\beta$	1.0178	1.0158	0.5734	0.9515	0.8249	0.9715	0.7861
	$\alpha + \beta$	1.0154	1.1261	1.1405	1.0353	0.8216	1.0419	0.7463
	$\alpha + 0.5\beta$	1.0110	1.3713	2.2095	1.2491	0.8179	1.2399	0.7047
ii) β -substituent (where $\alpha_X = \alpha + 2\beta$, $\beta_{CY} = \beta$)								
β_{CX}	α_Y	S_1^R	S_2^R	S_3^R	S_4^R	S_5^R	S_6^R	S_7^R
β	$\alpha + 2\beta$	0.6488	1.1863	0.5742	1.0571	0.8197	1.0962	0.7844
	$\alpha + \beta$	0.6487	1.3161	1.1443	1.1233	0.8160	1.1488	0.7456
	$\alpha + 0.5\beta$	0.6470	1.5852	2.2196	1.3147	0.8120	1.3242	0.7044

(2) Effect of β_{CY}

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1) The order of magnitude of S_r^R does not depend on β_{CY} for both α - and β -substituents, but it is determined by α_X .

2) For both α - and β -substituents, S_r^R increases as the absolute value of β_{CY} increases, irrespective of α_Y . The rate of increase becomes smaller in the order of $S_5^R > S_3^R > S_4^R$ for the α -substituent, and in the order of $S_2^R > S_5^R > S_4^R$ for the β -substituent.

From these results, the following may be concluded:

1) The site undergoing radical reactions depends on the electric negativity of heteroatoms. But the electric negativity of substituent bases and the overlapping of wave functions of heteroatoms with those of adjacent carbon atoms does not affect the reaction site. However, they are related to the reactivity (S_r^R itself). Thus, the radical reaction is strongly governed by the electric negativity of heteroatoms.

2) When heteroatoms possess great electric negativity (e.g., oxygen), they become reactive at the 5th position for the α -substituent, and at the 2nd position for the β -substituent. But for those having a smaller electric negativity -- such as selenium -- they become reactive

TABLE 17

THE VALUE OF S_r^R WHEN α_X , β_{CX} AND α_Y ARE CHANGED IN
MONOSUBSTITUTED, 6-MEMBERED RINGS

i) r-substituent (where $\alpha_X = \alpha + 0.5\beta$, $\beta_{CY} = \beta$)						
β_{CX}	α_Y	S_1^R	S_2^R	S_3^R	S_4^R	S_5^R
1.4β	$\alpha + 2\beta$	0.5903	0.7460	0.8790	0.7315	0.5561
	$\alpha + \beta$	0.6248	0.7442	0.9625	0.6898	1.0720
	α	2.4545	0.7940	4.5948	0.6368	15.9607
β	$\alpha + 2\beta$	0.8228	0.8420	0.8680	0.7779	0.5604
	$\alpha + \beta$	0.8732	0.8359	0.9436	0.7234	1.0608
	α	2.5315	0.9106	2.6780	0.6745	8.3832
0.8β	$\alpha + 2\beta$	1.0094	0.9259	0.8596	0.8260	0.5660
	$\alpha + \beta$	1.0668	0.9126	0.9286	0.7572	1.0544
	α	2.5418	0.9973	1.9698	0.7043	5.6198
ii) r-substituent (where $\alpha_X = \alpha + 2\beta$, $\beta_{CY} = \beta$)						
β_{CX}	α_Y	S_1^R	S_2^R	S_3^R	S_4^R	S_5^R
β	$\alpha + 2\beta$	0.5958	1.0176	0.8370	0.8685	0.5580
	$\alpha + \beta$	0.5921	0.9922	0.8817	0.7730	0.9758
	α	0.7873	1.1245	1.2029	0.7550	2.6620

at the 4th position for both α - and β -substituents. However, as in the case of selenium, the larger overlapping of wave functions due to interlacing with the d-orbital results in a smaller radical reactivity.

4.2 Monohetero, 6-Membered Ring Compounds

Using the same parameters as for S_r^E of monohetero, 6-membered ring compounds, we may compute S_r^R . The results are tabulated in Tables 15, 16, 17 and 18, and the conclusions are described below.

4.2.1 α -Substituent

(1) The maximum site of S_r^R depends on α_X , β_{CX} and α_Y , especially on α_X . When α_X is equal to $\alpha + 0.5\beta$, it is at the 3rd position, but is at the 6th position for $\alpha + 2\beta$.

(2) When $\beta_{CX} = \beta$, S_5^R decreases irrespective of α_Y as the absolute value of α_X increases, but S_4^R and S_6^R increase. The rate of increase is in the order of $S_6^R > S_4^R$. Since S_3^R is strongly influenced by α_Y , the effect of α_X depends on α_Y , and no general statements can be made. /676

(3) When $\alpha_X = \alpha + 0.5\beta$, S_5^R increases irrespective of α_Y as the absolute value of β_{CX} increases, but S_4^R and S_6^R decrease. The rate

TABLE 18

THE VALUE OF S_r^R WHEN α_Y IS CHANGED IN MONOSUBSTITUTED
6-MEMBERED RINGS (WHERE $\alpha_X = \alpha$, $\beta_{CY} = \beta$)

α_Y	S_1^R	S_2^R	S_3^R	S_4^R	S_5^R	S_6^R
$\alpha + 2\beta$	0.8700	0.8312	0.8812	0.7895	0.5730	
$\alpha + \beta$	0.9527	0.8283	0.9773	0.7485	1.1375	
$\alpha + 0.5\beta$	1.1656	0.8248	1.2057	0.7066	2.2011	

of decrease is in the order of $S_6^R > S_4^R$. Since S_3^R is strongly influenced by α_Y , the effect of α_X depends on α_Y , and no general statements can be made in this regard.

(4) Irrespective of α_X and β_{CX} , S_3^R , S_5^R and S_6^R decrease as the absolute value of α_Y increases. Since S_4^R is strongly influenced by heteroatoms, the effect of α_Y cannot be discussed in general.

4.2.2 β -Substituents

(1) The maximum site of S_r^R depends on α_X , β_{CX} and α_Y , especially on α_X , and β_{CX} . It is at the 2nd position when the absolute value of α_X becomes larger and that of β_{CX} becomes smaller. But it is at the 4th position when the absolute value of α_X becomes smaller and that of β_{CX} becomes larger.

(2) When $\beta_{CX} = \beta$, S_5^R slightly decreases, irrespective of α_Y as the absolute value of α_X increases, but S_2^R increases. Since S_4^R and S_6^R are strongly influenced by α_Y , the effect of α_X depends on α_Y , but it tends to decrease.

(3) When $\alpha_X = \alpha + 0.5\beta$, S_5^R slightly increases, irrespective of α_Y , as the absolute value of α_X increases, but S_2^R , S_4^R and S_6^R decrease. The rate of decrease is in the order of $S_2^R \sim S_6^R > S_4^R$.

(4) Irrespective of α_X and β_{CX} , S_5^R slightly increases as the absolute value of α_Y increases, but S_2^R , S_4^R and S_6^R decrease.

4.2.3 γ -Substituents

(1) The maximum site of S_r^R depends on α_X , β_{CX} and α_Y , especially on α_X . When α_X is equal to $\alpha + 0.5\beta$, it is at the 3rd position, but is at the 2nd position for $\alpha + 2\beta$.

(2) When $\beta_{CX} = \beta$, S_2^R increases irrespective of α_Y as the absolute value of α_X increases, but S_3^R decreases.

(3) When $\alpha_X = \alpha + 0.5\beta$, S_3^R increases irrespective of α_Y as the absolute value of β_{CX} increases, but S_2^R decreases.

(4) Irrespective of α_X and β_{CX} , S_3^R decreases as the absolute value of α_Y increases. Since S_2^R is strongly influenced by heteroatoms, the effect of α_Y cannot be discussed, in general.

From these results, the following conclusions can be drawn:

- (1) The maximum site of S_r^R is mainly dependent on α_Y and β_{CX} .
- (2) As the electric negativity of the substituent base increases, S_r^R at the o- and p-position decreases. The value of S_r^R at the m-position is not greatly affected by the electric negativity of the substituent base. The effect of the electric negativity of the substituent base on S_r^R depends on such factors as α_X , β_{CX} , the substituent base, heteroatoms, and the relative location of carbon atoms inside the ring.

As the overlapping of wave functions of heteroatoms with those of adjacent carbon atoms increases, and the electric negativity of heteroatoms increases, S_r^R at the 2nd, 4th and 6th position increases. But S_r^R at the 3rd and 5th position is not greatly influenced by heteroatoms.

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